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MARITIME COMMUNICATION EXPERIMENTS AND SEARCH-AND-RESCUE EVALUATIONS WITH THE NASA ATS-6 SATELLITE

Volume I - Summary

P.D. Engels, et al.

U.S. Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge MA 02142

FINAL REPORT

MAY 1978

U.S. DEPARTMENT OF TRANSPORTATION
United States Coast Guard
Office of Research and Development
Washington DC 20590

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16. Abstract

Maritime satellite communication experiments were conducted by ~~the Transportation Systems~~ This Center's Center using the NASA Applications Technology Satellite-Number 6 (ATS-6) from September ~~1975~~ 1974 through April 1975. The objectives were: to acquire a base of satellite technology knowledge applicable to ship-satellite-shore system design; and to demonstrate, by means of coordination among several ships, aircraft, and ground/shore control centers, some operational uses of satellites for ATC and SAR applications. Volume I provides a brief description of the ATS-6 experiments along with a description of the shipboard terminal equipment used in the experiments. Volume I also contains an executive summary of the experiments, a summary of the more significant results, major conclusions and recommendations for future activities.

The ATS-6 satellite maritime technology experiments have produced data which will be ~~utilized~~ in preparing specifications of ship terminals for possible future operational satellite systems. Evaluations were made of a shipboard antenna design, various types of voice, data, and ranging modulations, and the effects of multipath reflections off the sea and the ship superstructure. The safety demonstration experiments are expected to aid in evaluating the effectiveness of satellite communications in maritime safety-of-life-at-sea applications. In these tests, the satellite-to-ship link was used in a typical search and rescue incident along with the Emergency Position Indicating Radio Beacon ~~(EPIRB)~~ Buoy which initiated the distress alert.

Volume II contains the text of the report, together with references and an appendix listing contracts (268 pp.).

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PREFACE

The success of this program attests to the dedication and total commitment of all team members. Gratitude is expressed to the United States Coast Guard, Office of Research and Development, for their support in directing and sponsoring the Transportation Systems Center in the conduct of the ATS-6 experiments. We wish to specifically acknowledge the active support and technical assistance of Mr. John Carros/GDOE and LCDR R.E.Fenton and LT B.M. Chiswell formerly of the USCG, Office of Operations. We would also like to thank the National Aeronautics and Space Administration for making available the ATS-6 spacecraft along with all support facilities and personnel. In addition, the officers and crew aboard the participating USCG cutters, SHERMAN and GALLATIN, along with the TSC experimental crews manning the shipboard terminal, deserve a special note of praise for fine support and for enduring the hardships of shipboard life and long tedious hours away from home.

It is fitting to acknowledge the cooperation and contributions of all others in this activity, in addition to those specifically mentioned above:

European Space Agency
Federal Aviation Administration, National
  Aviation Facilities Experimental Center
Federal Republic of Germany
USCG, First and Third Districts
Officers and crew of the German ship OTTO HAHN

Finally, we wish to remember the late John Winchus of TSC who was responsible for assembly of the maritime shipboard terminal.

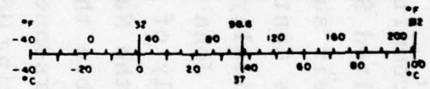
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

The U.S. Department of Transportation completed a series of tests in 1975 as part of the international ATS-6 experiment for Aeronautical and Maritime Satellite Communications. This internationally coordinated experiment used the U.S. National Aeronautics and Space Administration (NASA) Application Technology Satellite No. 6 (ATS-6) as the space segment. The United States Coast Guard (USCG) sponsored and directed the maritime satellite communications aspects of the experiment concerned with improvement of safety of life at sea. The DOT/USCG ATS-6 maritime experiments were planned to provide a comprehensive communication technology data base of satellite-to-mobile applications for maritime traffic service and improved search and rescue operations.

The general objectives of the U.S. DOT/USCG ATS-6 satellite experiments fell into three major categories: technical data acquisition, system demonstration, and the evaluation of potential operational benefits. The accomplishments of the ATS-6 experiments are stated as follows:

- Acquired technical data essential to the design of satellite communications systems for marine applications.
- Tested and rated components of potential new user electronics operating at L-Band (1600 MHz) for maritime services.
- The experiments validated the applicability of laboratory simulation of propagation phenomena. Scientists can now be assured of knowledge gained pertinent to propagation using the laboratory simulation without resorting to costly field tests.
- The advantages of a coordinated USCG and FAA effort using satellites to interconnect widely dispersed aircraft and ships in a search and rescue operation were clearly demonstrated. The usefulness of satellites in conjunction with emergency notification procedures was borne out in

demonstrating significant reduction in the distress alerting interval. Preliminary results were also obtained regarding direction finding operations with satellites.

- o Participated in an international and interagency coordinated experimental and technology sharing program. The results of these experiments are of direct interest to the following: International Civil Aviation Organization (ICAO), Intergovernmental Maritime Consultative Organization (IMCO), International Telecommunications Union and International Radio Consultative Committee (ITU/CCIR), International Union of Radio Science (URSI), and the Advisory Group for Aerospace Research and Development (AGARD) under NATO.

1. INTRODUCTION

Satellite telecommunications offers several potential advantages to the maritime community: 1) provides full oceanic coverage, 2) provides rapid access to any ship in the world, 3) provides satellite radio position determination, and 4) provides reliable communications with a link quality that is capable of supporting telephone-grade voice and high data-rate transmissions. The safety of life at sea is greatly enhanced by a maritime satellite system which provides improved distress alerting, more reliable communications, more accurate determination of the position of a vessel in distress, and improved rescue coordination. This report discusses the maritime satellite experimental program, sponsored by the U.S. DOT/United States Coast Guard, and carried out with the U.S. DOT/Transportation Systems Center using the National Aeronautics and Space Administration Application Technology Satellite, ATS-6.

1.1 BACKGROUND

The International Maritime Consultative Organization, Maritime Safety Committee (IMCO/MSC) has been active over the past six years in establishing the technical parameters of various maritime satellite system design alternatives. In addition it has helped formulate the organizational and institutional arrangements for cost-sharing, procuring, managing, and operating such a system. Although consideration is being given to a public correspondence (general telephone traffic) maritime communication satellite system with global coverage, the enhancement of the safety of life at sea is the paramount objective specified by the IMCO/MSC charter. The U.S. Coast Guard, representing the United States Government at the IMCO/MSC, is an active participant in the satellite discussions aimed at the enhancement of safety.

The practicability of a dedicated maritime satellite system for commercial worldwide shipping has been established through extensive tradeoff analyses, experimentation, technological

development, preliminary system design, testing and cost/benefit justifications. Experimental development is underway, and pre-operational systems are currently being implemented.[1] Operational systems are expected to follow within the next decade.

The success of maritime satellite communications in aiding a maritime distress alerting and rescue coordination system is predicated upon user participation, as is the case with existing distress services. To encourage and achieve participation in new satellite systems, performance improvements must be achievable with low-cost maritime mobile equipment. To date, system feasibility has been demonstrated through detailed analysis and evaluation of of system parameters, tradeoff designs, and parametric measurements of shipboard equipment and system performance.(2) Satellite operational applications must be clearly demonstrated, however, as a necessary step toward operational maritime satellite systems to serve the maritime shipping community as well as improve maritime safety.

1.2 OBJECTIVES AND PARTICIPANTS

The World Administrative Radio Conference for Space Telecommunications (WARC-ST) allocated a portion of the L-Band spectrum for joint aeronautical and maritime use. Search and Rescue (SAR) coordination has been identified by both IMCO and the International Civil Aviation Organization (ICAO) as a leading candidate for use of this spectrum.

In May 1974, the National Aeronautics and Space Administration launched and deployed the sixth in a series of Applications Technology Satellites (ATS-6). With the test system capability provided by ATS-6, as illustrated in Figure 1-1, the maritime and aeronautical users were able to evaluate the potential of L-Band satellite communications. In accordance with test plans[3] prepared by the participants and coordinated by NASA, experimenters using ATS-6 gathered approximately 1000 hours of L- Band data in the period from July 1974 to April 1975.

With future system development planned for the 1550-1650 MHz frequency band, new L-band shipboard equipment must be developed

FIGURE 1-1. DOT/USCG EXPERIMENT USING THE NASA ATS-6 SATELLITE

and evaluated. Experiments were therefore conducted to obtain a technology data base for parametrically evaluating shipboard antenna designs and various types of modulation-demodulation (modem) techniques for voice, data, simultaneous voice and data, and ranging. measurements were also conducted to characterize the effects of multipath reflection of signals from the superstructure of a ship and from the sea surface under varying sea state conditions.

The DOT/USCG maritime satellite experiment objectives were:

a. To measure and characterize multipath properties of the ship-to-satellite L-band channel to provide the following:
   - Verification of an analytical model for the ship-to-satellite link in the presence of multipath reflections.
   - Validation of an electrical analog laboratory instrument designed to simulate the ship-to-satellite communication channel.

b. To evaluate communications utilizing alternative modulation-demodulation (modem) techniques and hardware for the transmission of voice, digital data, and position determination information.

c. To evaluate a hemispherical coverage antenna (4 dB) and a medium gain (15 dB) experimental antenna in conjunction with various stabilization and control modes.

d. To evaluate relative range techniques utilizing satellites for position determination applications.

e. To demonstrate the life saving potential to Search and Rescue operations made possible by a satellite aided distress and communications coordination system.

Along with the technology data acquisition experiments, some operational evaluations were planned with ATS-6 in cooperation with the various participants in the program. The DOT/USCG, with the support of the DOT/Transportation Systems Center, coordinated and conducted a simulated search and rescue (SAR) incident using ATS-6 in order to demonstrate the potential time and life saving

benefits of satellite SAR operations.

The international agencies involved in the ATS-6 experiments, along with their respective mobile and stationary terminals (aircraft, ships, and land) are shown in Table 1-1.

TABLE 1-1 PARTICIPANTS COOPERATING IN THE ATS-6 TESTS

Agency	Mobile Description
FAA/TSC	1-KC135 airplane
ESA (aircraft)	1-Comet airplane
Canada, Ministry of Transport	1-Lockheed Jetstar
DOC/MARAD	2-cargo ships - AMERICAN ALLIANCE and LASH ATLANTICO
USCG/TSC	2-cutters, GALLATIN and SHERMAN
ESA (Maritime)	German ship, OTTO HAHN
Federal Republic of Germany	Buoy-Emergency Position Indication Radio Beacon (EPIRB)
The ground and support facilities utilized in these experiments were:	
NASA/Goddard Space Flight Ctr.	Applications Technology Satellite Operations Control Center
NASA/Rosman	ATS-6 Ground Station Earth Terminal
National Aviation Facilities Experimental Center	Experimental Oceanic Air Traffic Control Center
Transportation Systems Center	ATS-6 Technology Experiment Coordination Center
USCG/New York City	Rescue Coordination Center and the Automated Mutual-Assistance Vessel Rescue System (AMVER)

A test plan was coordinated by NASA from test proposals received from the DOT/Transportation Systems Center (TSC), Federal Aviation Administration (FAA), U.S. Coast Guard (USCG), Canadian Ministry of Transport (MOT), European Space Agency (ESA), and the U.S. Maritime Administration (MARAD). Coordination provided by NASA allowed joint use of the satellite and effective use of the allocated satellite time.

2. EXPERIMENT DESCRIPTION

2.1 LINK CONFIGURATIONS

The overall configuration for the ATS-6 experiments is illustrated in Figure 2-1. For the DOT/USCG experiments, a two-way simultaneous communication channel between the NASA ground station at Rosman, NC, and a USCG cutter (either the GALLATIN or the SHERMAN) was established through ATS-6. Telephone land lines were set up between Rosman and various remote ground facilities such as the NASA operations center, DOT Headquarters, DOT/TSC, USCG Rescue Coordination Centers, FAA/NAFEC, etc. The communications link from the satellite consisted of a frequency division multiplex of various combinations of modulations which were transmitted as subcarriers on the nominal 1550 MHz carrier. The links between the ground and the satellite were at C-band. The signal quality over the C-band uplink was sufficient to consider the link transparent for the tests. All measured propagation phenomena, therefore, pertained exclusively to the L-band ship-to-satellite channels.

2.2 SHIPBOARD TERMINAL EQUIPMENT

The shipboard communications terminal used for the DOT/USCG was a self-contained small laboratory housed in a transportable shelter as shown in Figure 2-2. The shelter was strapped down to the helicopter deck of the U.S. Coast Guard cutter. During the ocean test campaigns, the cutters were assigned to the experiment and operated in conjunction with pre-determined experiment plans. All communications, analysis, and maintenance equipment was installed and operated in the shelter.

The shipboard communications terminal was designed to operate with an experimental medium gain antenna. The antenna had a nominal gain of 15 dB and was capable of various modes of stabilization and control as follows:

a. Autotrack Mode - The antenna had a self contained monopulse tracking system which locked to the L-band satellite transmission.

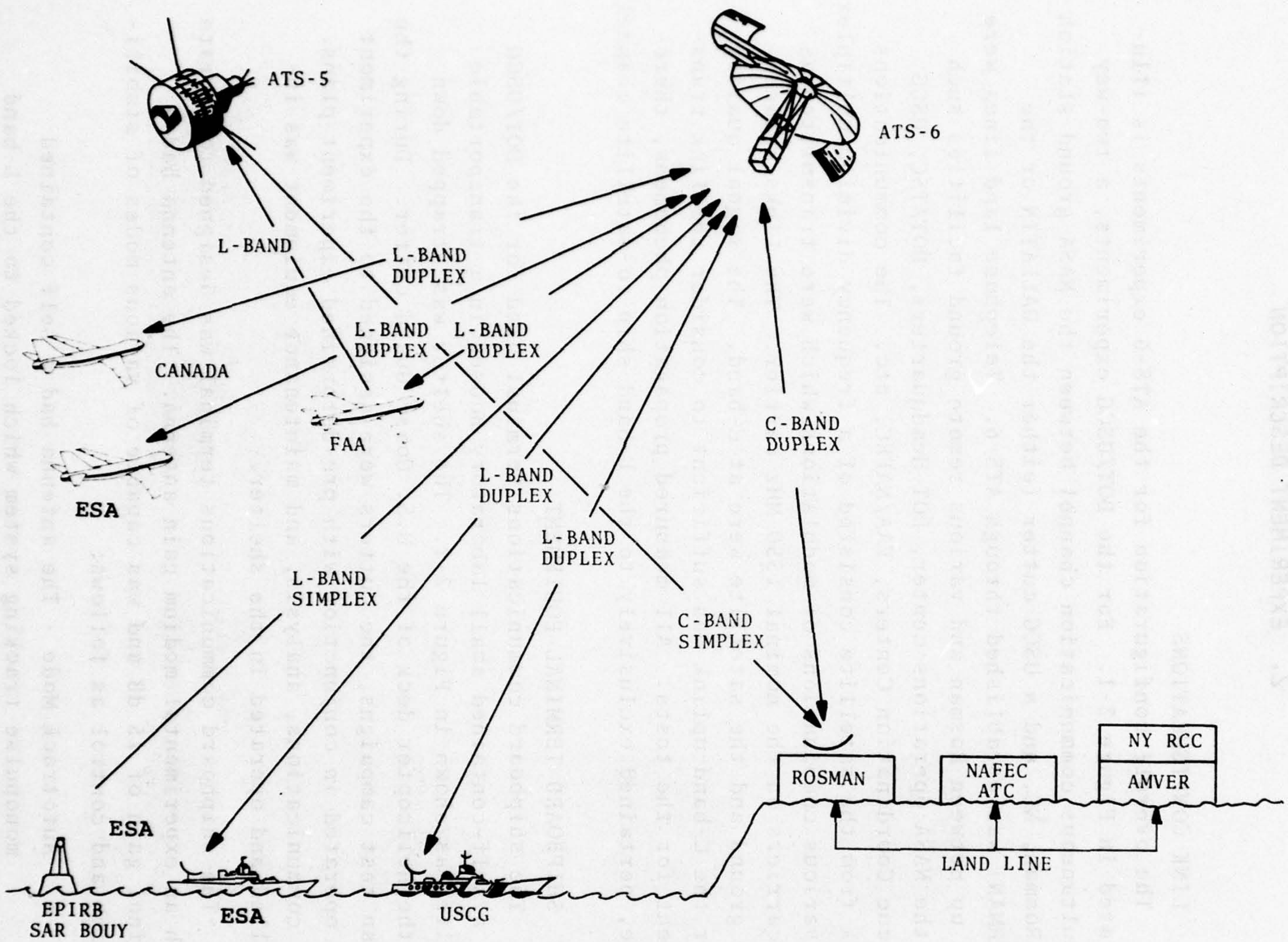


FIGURE 2-1. COORDINATED ATS-6 SATELLITE EXPERIMENT CONFIGURATION

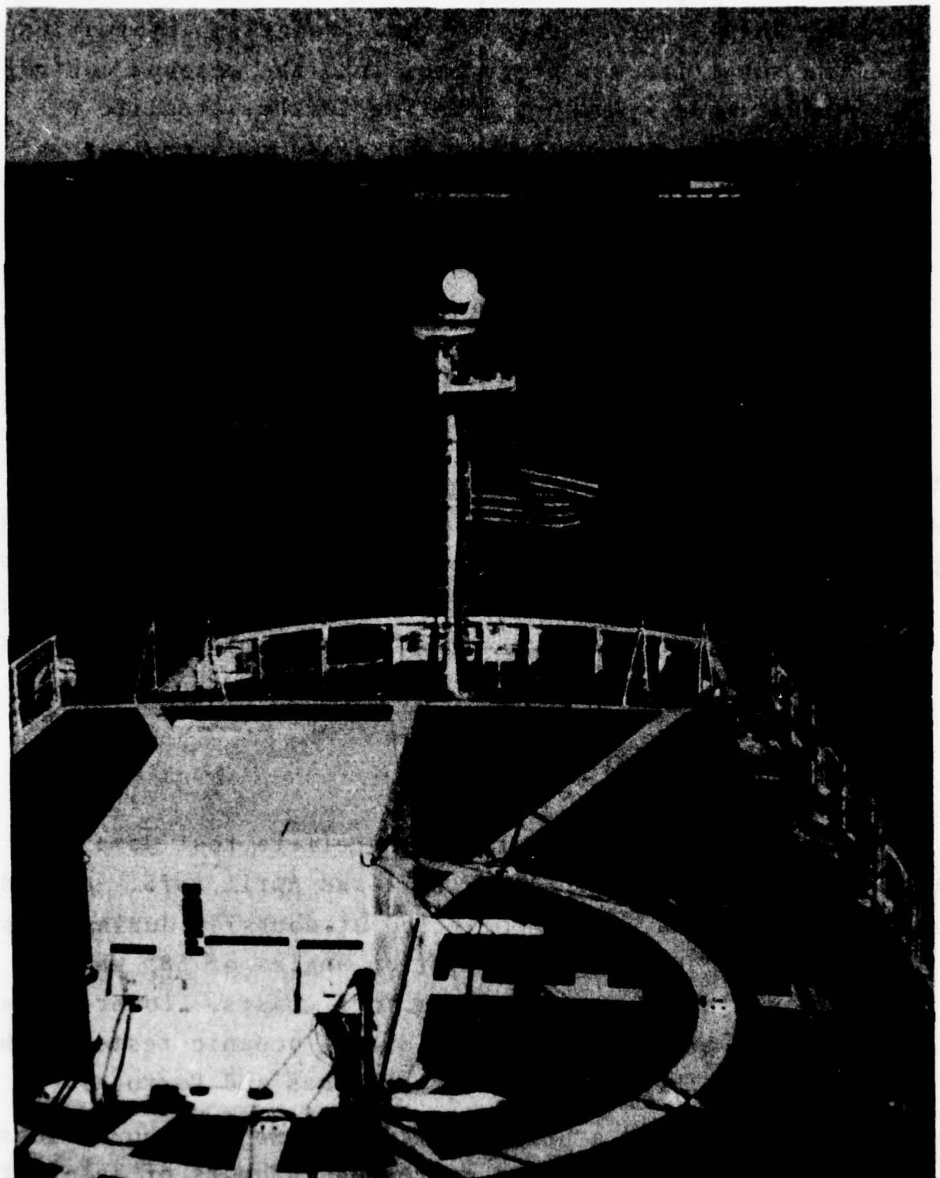


FIGURE 2-2. DOT/USCG PORTABLE TERMINAL LABORATORY SHELTER

b. Slave Mode - The antenna was open-loop controlled by the ship's gyrocompass system. Pointing information to the satellite was programmed into the antenna controller.

c. Manual Mode - Antenna pointing to the satellite was accomplished manually via the antenna controller which permitted the antenna to be oriented with respect to deck coordinates. No stabilization was provided and antenna pointing remained fixed relative to the deck. The moderately wide 3 dB beam width (35°) made communications possible in this mode for relatively calm seas and fixed headings.

The experimental antenna was mounted on a specially erected mast about 15 feet above the aft end of the helicopter deck. This location gave the antenna a clear view of the satellite without shipboard obstructions except in orientations where the satellite was within an arc of ±11° off the bow with elevation angles of 28° or less. The location was high enough to prevent clutter reception and also high enough to allow communications to the satellite at low elevation angles.

2.3 TEST CONDITIONS

Approximately 105 hours of ship-satellite test data were acquired at sea between September 1974 and April 1975. An additional 23 hours of data were collected at dockside during this period. Data was obtained at elevation angles of 38° while cruising off the New England and New York coasts. Lower elevation angle data (0 to 10°) was obtained during oceanic tests in the North Atlantic in the vicinity of the Azores and Portugal.

Table 2-1 provides a brief summary of the test conditions and the amount of data gathered,expressed in hours of satellite time. Table 2-2 details the total technology test hours scheduled and compares this with the actual data acquired during the program. Since two types of tests,i.e., demonstration and modem tests, were sometimes run on the same day, the total number of test days shown in Table 2-1 (47) is less than the total number of tests listed

(50). Additionally, the test hours listed refer to "satellite time" and do not account for simultaneous operation of several communications modems using the same received signal.

TABLE 2-1 USCG/TSC ATS-6 EXPERIMENT - SUMMARY OF TESTS

Range of satellite elevation angles: 2^0 to 38^0

Wave heights: calm seas to 30 to 40 foot seas

Wind velocities: calm to 70 knots +

Total numbers of test hours: 142.2

Demonstration test hours 15

Technology test hours 127.2

Total number of test days: 47 (41 at sea)

TEST	IN PORT	AT SEA	TOTAL
Modem	5	28	33
Antenna	-	11	11
Demonstration	3	3	6

TABLE 2-2 USCG ATS-6 EXPERIMENT -- DETAILED SUMMARY OF TECHNOLOGY TEST HOURS

ACTIVITY	TOTAL SCHEDULED	TOTAL ACQUIRED
Modem testing		
Voice	36.3	35.4
Data	32.1	37.9
Data, circular course*	11.6	5.8
Voice/Data	9.7	8.6
Ranging	13.5	13.5
	103.2	101.2
Pseudo-Noise Multipath	9.3	10.6
Antenna tests	11.2	15.4
Totals	123.7	127.2

*Data gathered when the ship was following a circular course such that the satellite-ship geometry was undergoing continuous change and hence signal scattering and possible shadowing due to the ship's superstructure are not constant.

3. TEST RESULTS

3.1 CHANNEL CHARACTERIZATION

The channel measurements used to characterize multipath operation were accomplished in two modes. First, the transmission from Rosman included a continuous wave (CW) signal which was received at the ship and recorded. The multipath component on the signal was measured simultaneously with the antenna and modem tests. Multipath data collected in this way provides channel parameters for correlation of propagation conditions with measured modem and antenna performance. The narrowband channel measurement experiment provided complete channel characterization data for channel bandwidths less than 200 kHz.

In addition, the shelter equipment included a wideband transmitter and modulator. With this equipment, wideband (10 MHZ) channel probing signals consisting of pseudo-noise modulations were sent through the ATS-6 satellite back to the Rosman facility. The received wideband probing signal was analyzed at Rosman by a multiple channel correlation instrument, the satellite aeronautical channel prober (SACP), which was implemented for similar aeronautical satellite tests and adapted for the maritime tests.These SACP tests were designed to determine the multipath delay spreads of the channel along with many other parameters. The wideband measurements showed that for all observations of this experiment, the delay spread was less than 100 nanoseconds. It has been shown that when the inverse of the delay spread is much wider than the signal bandwidth, a narrowband propagation model adequately characterizes the channel.[4] The experimental results justify the use of the narrowband channel/model and CW data for all system designs which use channel bandwidths less than 200 kHz.

The channel characterization data collected during the ATS-6 maritime satellite tests also supports the conclusion that the reflected multipath is diffuse. A typical carrier-to-multipath (C/M) ratio before antenna discrimination is 8 dB. The C/M = 8 dB holds for a wide range of sea state conditions and satellite eleva-

tion angles. In addition, it was found that the multipath energy appears to arrive from a broad region on the ocean's surface near the horizon rather than from the multipath specular reflection point. The comparison of the measured multipath characteristics with the analytical model presented in Volume II of this report is shown in Table 3-1. It can be concluded that the narrowband analytical model parameters were confirmed by measured experimental results.

TABLE 3-1 COMPARISON OF ANALYTICAL AND TEST RESULTS

Multipath Parameter	Worst Case for Analytical Model (30^0-40^0 beamwidth)	Worst Case Measured Value (35^0 beamwidth)
Relative Delay	0-70 ns max	<100 ns
Delay Spread	0-200 ns max	<100 ns
Relative Doppler	0	0
Doppler Spread	0-30 Hz	<10 Hz
Relative Power	-5 dB (avg.)	-6 dB (avg.)

3.2 ANTENNA TESTS

The objective of the antenna experiment was to evaluate performance of a medium gain antenna (15 dB) having various modes of stabilization. The evaluation consisted of measuring pointing error for three modes of stabilized operation as follows:

a. Slaved to a 3-axis inertial reference (the ship's gyro)
b. Automatic tracking using monopulse tracking techniques.
c. Manual pointing of the antenna in the direction of the satellite (no stabilization was used).

The measurements were made under a variety of ship motion, sea state and multipath conditions. Table 3-2 summarizes the antenna test conditions experienced during the 1975 test series.

TABLE 3-2 SUMMARY OF ANTENNA TEST CONDITIONS - SPRING 1975

Wave heights	1 ft to 20 ft
Satellite elevation angles	8.7° to 39°
C/M ratios	6.9 dB to 21.2 dB*
Heading standard deviation, σ_H	0.6° to 3.6°
Roll standard deviation, σ_R	1.1° to 5.2°
Pitch standard deviation , σ_P	0.5° to 2.0°

*The carrier-to-multipath power ratio, C/M, ranged from 10.3 dB to 13.1 dB during autotrack measurements.

The following observations are drawn from the data presented in Volume II of this report.

1. The slave mode of antenna stabilization generally gave performance superior to that of the autotrack mode.

2. The maximum total pointing error never exceeded 8.4° in the slave mode nor 14.8° in the autotrack mode. Thus, the slave mode of operation was capable of maintaining the satellite within the -1 dB contour of the antenna pattern (approximately ±11° off boresight).

3. Reflections and shadows from the ship's superstructure were encountered at low elevation angles with the antenna-satellite geometry such that the superstructure was within the antenna beam. Fades of 8 to 10 dB were encountered when the view of the satellite was obscured by the superstructure. The autotrack system was generally able to maintain lock during turns when the aft mast of cutter passed through the line-of-sight to the satellite. During such turns the view of the satellite was obscured for approximately three seconds producing signal fading typified by that shown in Figure 3-1. A ship-to-satellite link, under conditions where the received signal was near the thermal noise threshold, would incur an outage under those satellite-ship orientations where the superstructure obstructed the direct path to the satellite. This suggests careful positioning of the shipboard antenna so as to min-

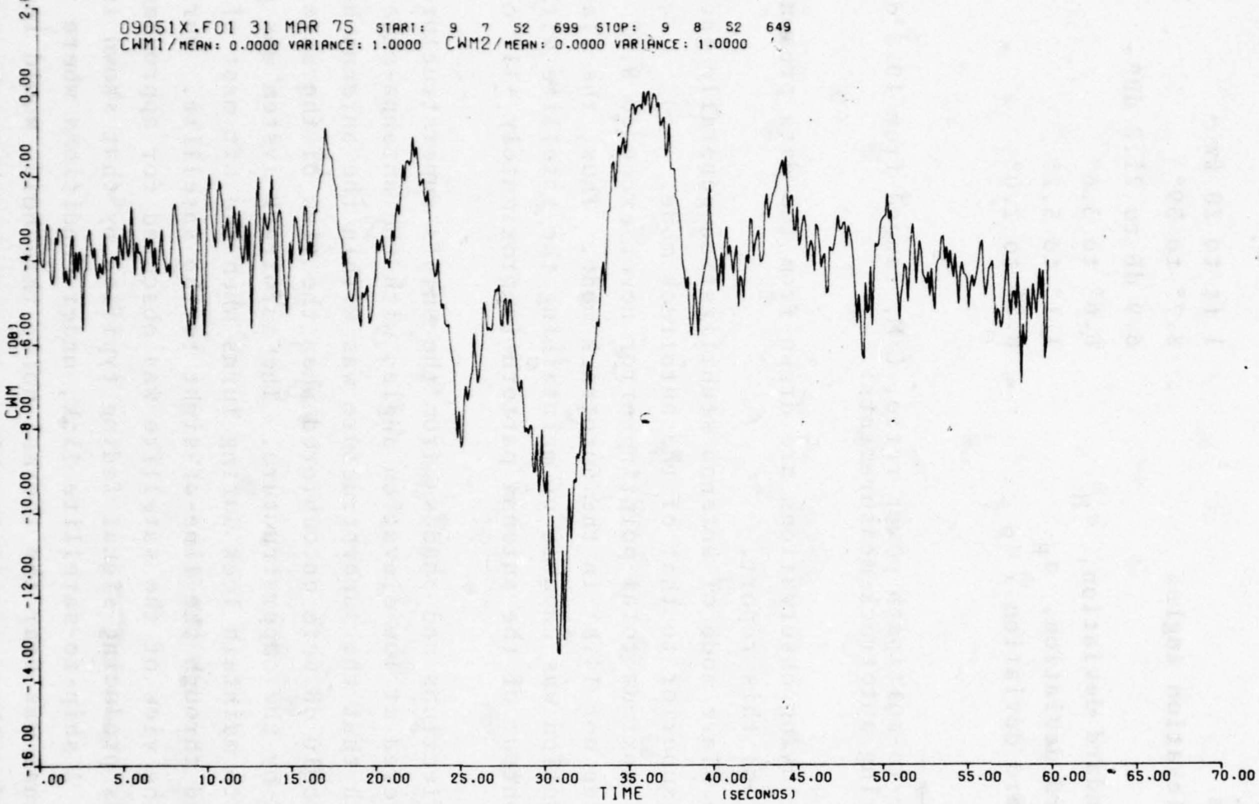


FIGURE 3-1. TYPICAL FADE CAUSED BY SHIP'S SUPERSTRUCTURE

imize such obstructions.

Although this report presents no quantitative data for fixed antenna pointing (manual mode), evaluation of data taken in either the slave or autotrack modes indicates that in many instances manual pointing would have been adequate to maintain the satellite within the antenna beamwidth. It should be noted that this form of manual pointing would be suitable only for constant headings since the antenna would have no provision for automatic tracking of the satellite in azimuth during turns.

Data was acquired to evaluate an antenna with a nominal gain of 4 dB over a 160° solid angle in the upper hemisphere. These tests were intended to provide data representative of an omni antenna element as might be used in a low cost shipboard application. Unfortunately, anomalous performance for the 4 dB omni was revealed upon examination of the data after the experiment was concluded. The performance observed indicated an antenna malfunction which was confirmed when it was learned that the antenna was improperly connected because of an error in polarization labeling. Consequently, none of the data obtained for the omni antenna is representative of the performance expected. Therefore, no omni data is presented and conclusions are not drawn in this report regarding omni antenna performance in satellite to ship links. It is recommended that future tests be conducted to fill this void.

3.3 VOICE AND DATA MODEM TESTS

Modulation techniques for maritime satellite services have not been standardized and are therefore under investigation by various countries. Consequently, several types of modems were evaluated as part of these ATS-6 experiments. The technical characteristics of the voice modems tested are summarized in Table 3-3. The Hybrid I modem combined suppressed carrier amplitude modulation of the voice signal in phase quadrature with differentially encoded phase-shift keyed (PSK) modulation of the digital data followed by hard limiting. This process results in a low deviation phase modulation for voice and differentially encoded PSK for digital data and provides the capability of simultaneous transmission of

TABLES 3-3 TECHNICAL CHARACTERISTICS OF VOICE MODEMS

Modem/ Manufacturer	Modulation Type	Demodulation Type	Voice Processing*	RF Bandwidth	Voice Bandwidth	C/N_o Threshold
P-M/PSK (Hybrid #1) Bell Aerospace	Sup. Carr. A.M., added to Quad. Carrier and Hard Limited	Narrow band PLL for voice and Costas Loop for data.	Pre & De-emphasis and compression at modulation*	Less than 10 kHz	300 to 3500 Hz	38 dBHz
PDM/PSK (Hybrid #2) Magnavox Research Labs.	PDM with suppressed carrier, 9600 samples per second PSK carrier	PSK with Costas Loop for Carrier and PDM for voice signal demodulation	Pre & De-emphasis and compression at modulation	Approx. 20 kHz	300 to 3500 Hz	38 dBHz
ADVM Bell Aerospace	Adaptive Δ modulation PSK with pilot tone reference, 19.2 kb/s rate	Digital - PSK with Adaptive Δ Analog - PLL for Carr. and Quad. modulation with interrogator	Some pre-emphasis	40 kHz minimum	300 to 3500 Hz	Analog - 38 dBHz Digital - 41 dBHz
ANBFM Bell Aerospace	Low Deviation Index FM ($\pm$ 1.5 kHz)	Modulation tracking PLL Demod with Adaptive Closed Loop BW	Same as Hybrid #1	Less than 10 kHz	300 to 3500 Hz	39 dBHz

*Companding Not Used: Voice Modulation Compression Ratio Peak/rms = 12 dB

voice and data. This modem could also be switched so as to transmit and receive adaptive variable slope delta modulation (ADVM) for voice at a bit rate of 19.2 kb/s. The demodulation process provides for either digital or analog processing of the 19.2 kb/sec. data stream. Analog processing provides improved intelligibility over digital matched filtering below 46 dB-Hz carrier-to-noise power density ratio. It should be noted that voice and data can not be transmitted simultaneously when the modem is used in the ADVM mode. Hybrid II modem used 9.6 kb/s suppressed clock pulse duration modulation of digitized voice and differentially encoded phase shift keyed modulation for digital data. It also had the capability of simultaneous transmission of voice and data combined in phase quadrature on the same carrier and at constant envelope. A third modem was also tested which had adaptive narrow-band frequency modulation (ANBFM) for voice and differentially encoded phase-shift keyed modulation for data. Simultaneous voice and data operation was not possible with this third modem.

These modems were first evaluated under laboratory conditions using the TSC multipath simulator[5,6,7] then field tested under typical operating conditions of satellite elevation angles, carrier-to-noise and carrier-to-multipath ratios, and varying sea states. Performance capabilities were demonstrated for voice and 1200 bps digital data transmission in conjunction with the medium gain (15 dB) directive antenna. Voice modem performance was measured in terms of phonetically balanced 400 word intelligibility.

Comparisons of the voice modem results obtained for the satellite-to-ship experiments are shown in the composite plot of Figure 3-2. The data points presented in this figure are averages of all the data for all parametric conditions shown in Table 3-1 for each modem. The modems were tested simultaneously over the links with each modulation on a different subcarrier of a frequency division multiplex spectrum. Averaged over the range of conditions encountered, the Hybrid I modem consistently had the highest scores of all modems tested. The ADVM and Hybrid II modems ranked second and third, respectively. The average voice intelligibility of the Hybrid I modem in the voice-only mode exceeded 80 percent for

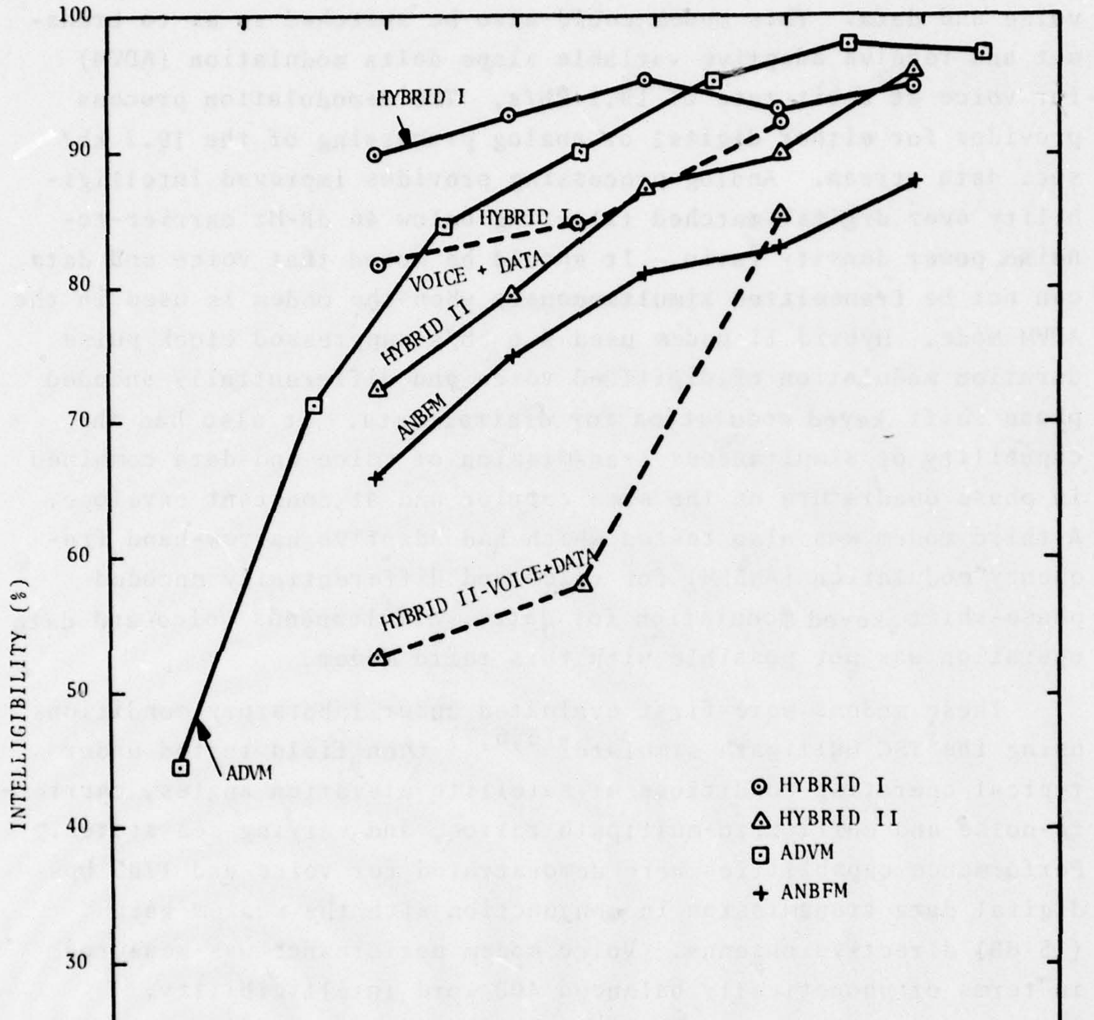


FIGURE 3-2. SUMMARY OF VOICE PERFORMANCE

carrier-to-noise density ratios of 43 dB-Hz or higher. Above 46 dB-Hz, Hybrid I achieved intelligibility scores of approximately 95 percent. For C/N_o greater than 43 dB-Hz, the performance of all three modems is within 10 percent wordscore intelligibility. However, ADVM and Hybrid II appeared to experience a definite threshold at or below C/N_o = 43 dB-Hz. The performance of the Hybrid I modem when operated in the voice-plus-data mode was greater than 80 percent intelligibility at 43 dB-Hz and reached 90 percent intelligibility at 46 dB-Hz. Examination of voice modem data collected over the full range of satellite elevation angles and sea states revealed that the voice modems were not susceptible to degradation due to multipath. This finding agrees with the results of extensive laboratory testing using the TSC multipath channel simulator. Voice modem performance is primarily a function of received carrier-to-noise density ratio for all test conditions. This held true even for situations wherein measured levels of multipath were only 5 dB below the carrier level.

Plots of the data modem performance obtained in the satellite-to-ship tests for the Hybrid I modem are presented in Figure 3-3. Results are plotted for a data rate of 1200 bps. The Hybrid I data modem results shown are typical of the performance for all of the data modems tested since they were all similar in basic modulation and design. Hence only the one set of results from Hybrid I is presented. The performance of the modem in terms of bit error rate is plotted vs. carrier-to-noise density (C/N_o) with measured C/M (carrier/multipath) as a test parameter. The multipath was measured simultaneously on a separate subcarrier. Each C/M value is noted adjacent to the modem performance data point. A theoretical curve for optimum demodulation in the presence of Gaussian noise only is included for comparison. This represents the best achievable performance of the modem since no multipath is present.

Superimposed on the data modem performance of Figure 3-3 are laboratory measured results obtained using the multipath channel simulator facility at TSC.[7] The laboratory results are the solid curves shown in Figure 3-3 with each plot representing the

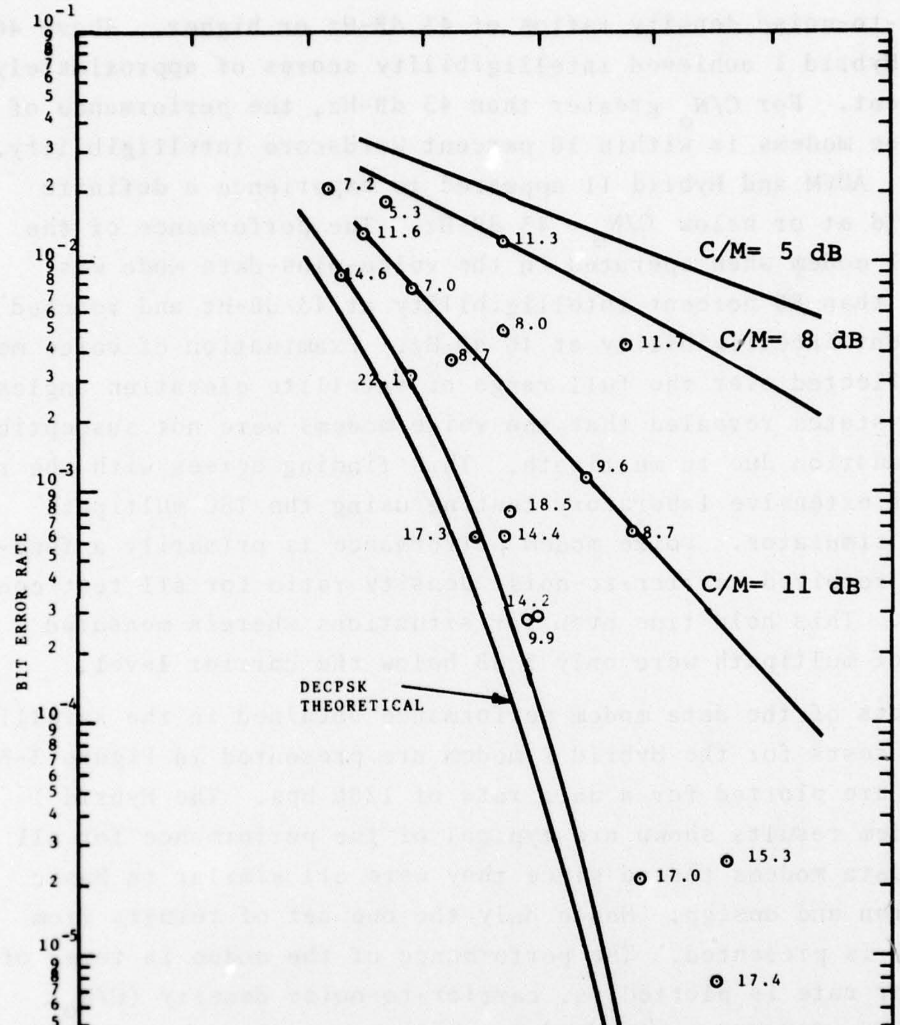


FIGURE 3-3. PERFORMANCE OF HYBRID I DIFFERENTIALLY ENCODED COHERENT PSK MODEM TESTED OVER THE ATS-6 SATELLITE TO SHIP LINK

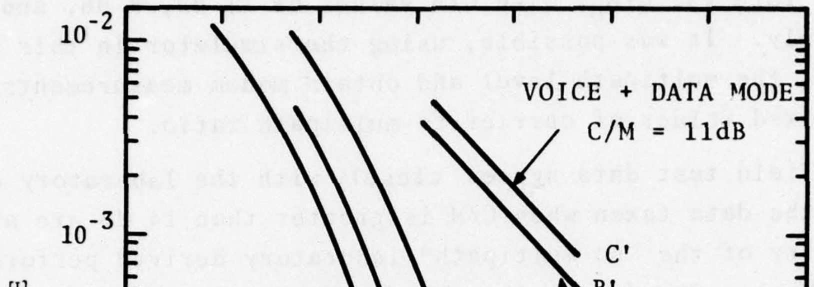
bit error rate vs. C/N_0, with C/M values of 11 dB, 8 dB, and 5 dB, respectively. It was possible, using the simulator in this way, to control the multipath level and obtain modem measurements at several fixed values of carrier-to-multipath ratio.

The field test data agrees closely with the laboratory data. For example, the data taken when C/M is greater than 14 dB are all in the vicinity of the "no-multipath" laboratory derived performance curve ($C/M=\infty$). The data collected when C/M was below this value are approximately in the region between the C/M = 11 dB and C/M = 8 dB performance curves. Field data points above the C/M = 8 dB laboratory derived curve have not been plotted. Data points, for C/M less than 8 dB were erratic because the modem and data error analyzer would not remain in lock to allow counting errors. Similar effects were observed during laboratory testing of the modems.

Data modem performance in the voice-plus-data mode for the Hybrid I modem is presented in Figure 3-4. The curve shows that the presence of the quadrature voice signal causes minor performance degradation of 1 to 2 dB (in the absence of multipath)compared to performance with data only. At 43 dB-Hz, this modem provided a bit error rate of 5×10^{-6} with voice on the quadrature channel. The modem simultaneously provided an average voice intelligibility of 84 percent. Carrier-to-multipath values in the range of 10 to 12 dB produced similar results in the voice-plus-data mode as in the data-only mode. It should be noted that the voice performance in either the voice-only or voice-and data mode compared closely regardless of the multipath level encountered.

3.4 RANGING MODEM TESTS

A digital tone ranging modem was developed at TSC. To evaluate this technique the system was configured as a one-way ranging system. The time delay of the transmitted signal was measured relative to a local onboard precision clock. These measurements at C/N_0 varying between 38 and 44 dB-Hz and various C/M determined the extent of random errors caused by multipath and noise. Timing and bias errors were not measured, however, these variables are common to all systems and are not modulation dependent.



LEGEND:

A - Theoretical DECPSK -- No multipath

B - DECPSK performance -- Data-only mode, TSC Simulator no multipath

C - DECPSK performance -- Data-plus-voice mode, TSC Simulator no multipath

B' - DECPSK performance -- Data-only mode C/M = 11 dB, BW= 10 Hz

C' DECPSK performance -- Data-plus-voice mode C/M = 11 dB, BW = 10 Hz

FIGURE 3-4. EFFECT OF MODERATE MULTIPATH ON DECPSK DATA PERFORMANCE OF HYBRID I MODEM TESTED ON TSC MULTIPATH CHANNEL SIMULATOR

The significant results obtained during the ranging modem tests are plotted in Figure 3-5. The figure shows the performances achieved with the modem operating with a clock of 156 kHz and a clock of 20 kHz.

One set of solid curves represents the theoretical performance estimates for these operating modes. Data obtained with the TSC channel simulator for the same operating modes are also presented in Figure 3-5 for the purpose of comparisons of ATS-6 and laboratory results. The ATS-6 test results are in general agreement with the laboratory simulator tests. The precision measured for the narrow-band, 20 kHz, code was about 200 to 500 feet for the range of signal levels used with the ATS-6 (36 - 44 dB-Hz). The precision of the wide-band, 156 kHz, code ranged from 20 to 80 feet over the same signal level range.

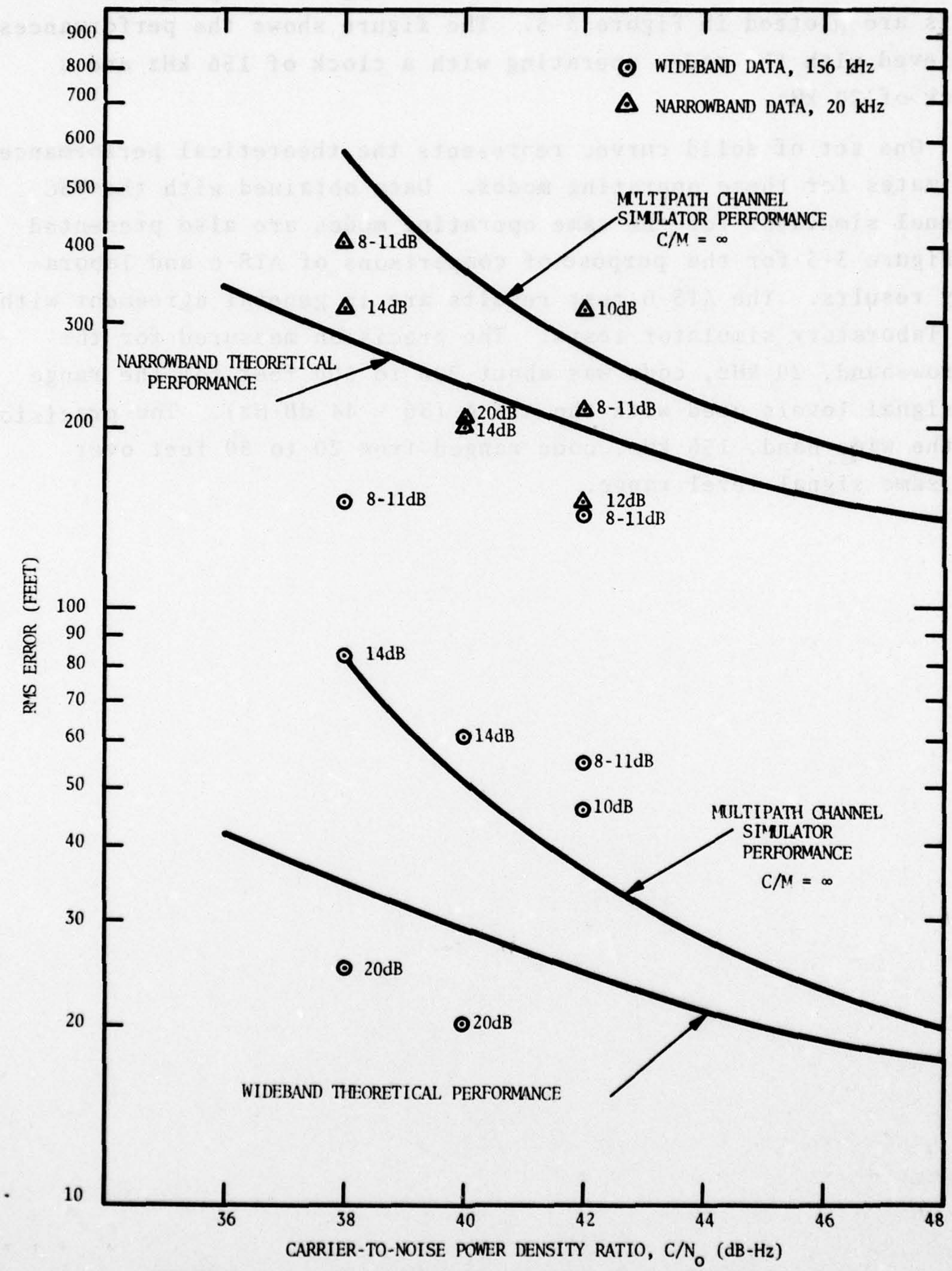


FIGURE 3-5. PERFORMANCE OF THE TSC RANGING MODEM TESTED OVER THE ATS-6 TO SHIP LINK

4. MARITIME SAFETY COMMUNICATIONS EVALUATIONS

Future application of satellite communications to distress and safety will require evaluation of operational techniques and/or technical performance of selected equipment. The following tests were therefore conducted with ATS-6.

a. Selective calling
b. Low-speed teleprinter/data
c. Ship-aircraft search and rescue

A digital selective calling (SELCAL) system was planned for maritime use in MF, HF, and VHF terrestrial communications. Tests were conducted to determine the utility of such a system for L-band signaling. The SELCAL performed well at C/No above 42 dB-Hz.

To demonstrate typical operational radio-teleprinter equipment interfaces with satellite systems, General Electric Terminet-300 teleprinters were installed on the GALLATIN and linked via ATS -6 to the Rosman Earth station. Teleprinter performance was found acceptable at 40 dB-Hz and higher. Automatic control of the receiving data terminal was also demonstrated.

The ship/aircraft search and rescue (SAR) demonstration used the same equipment as the technology tests. A detailed scenario was developed which focused on the simulation of a SAR incident. The simulated SAR incident was initiated when an L-band Emergency Position Indicating Radio Beacon (EPIRB) buoy was deployed in the general vicinity of the Azores Islands. The EPIRB buoy[8,9] developed by the Federal Republic of Germany, was provided by ESA. The "distressed vessel's" call sign was transmitted by the EPIRB buoy to the NASA Rosman Earth Station via the ATS-6 satellite. Additionally, the EPIRB buoy provided a homing beacon on the international distress frequency of 2182 kHz. Full duplex voice communication was established at L-band via the ATS-6 satellite among the various participants (sea, air, and land) in the SAR incident. The SAR participants were the USCG cutter GALLATIN, the West German ship OTTO HAHN, the FAA KC-135, and the ESA Comet

aircraft. The participating ground facilities were FAA/NAFEC, NASA Rosman, and the U.S. Coast Guard Rescue Coordination Center (RCC) in New York City. An initial estimate of the "distressed vessel's" position was computed by the Automated Mutual Assistance Vessel Rescue System in New York City. Search aircraft and ships were vectored to the scene by the USCG "SAR Controller" at the Rescue Coordination Center.

The salient features of this demonstration were the immediate notification of RCC that a particular vessel was in distress, the calculation of its probable position, and the coordination of the entire air and sea search operation by a single agency aided by full duplex satellite communications among all search parties. The demonstration was without precedent with regard to the use of satellites in SAR, and, moreover, was highly successful. The results of the maritime safety demonstration confirmed that safety of life at sea will be significantly enhanced when future maritime satellite systems become operational.

5. CONCLUSIONS

The major technical findings of the ATS-6 satellite maritime experiment program can be summarized as follows:

a. High quality voice performance was achieved using the Hybrid I modem. Performance of this modem exceeded 80 percent voice intelligibility down to 40 dB-Hz and exceeded 90 percent intelligibility for carrier-to-noise power density ratios above 46 dB-Hz. Ninety percent voice intelligibility corresponds to telephone voice quality communications.* Hybrid I performance was superior to that of all other voice modems tested.

b. In the voice plus data mode (simultaneous transmission of voice and data on a single carrier), the Hybrid I modem voice intelligibility exceeded 80 percent from 40 to 48 dB-Hz. This modem will simultaneously provide a 1200 b/s data stream with a bit error rate of 1×10^{-5}, for C/No above 43 dB-Hz.

c. Under all conditions the performance of both the Hybrid I and Hybrid II modems was closely consistent with theoretical predictions and laboratory simulations, including degradation due to multipath. Voice modem performance was essentially non dependent on multipath level.

d. Multipath was worst at low elevation angles and high sea states; however, it was present under almost all test conditions. The observed multipath was predominantly diffuse. In addition, it appeared to fit an empirical model in which the majority of the energy was reflected near the horizon rather than the point of geometrical specular reflection. The measured diffuse multipath energy was typically 6-9 dB below the incident (direct path) signal.

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*This correspondence is based upon an interpolation of data for phonetically balanced (PB) word lists of 250 words and 1,000 words.[10,11] The ATS-6 tests were run with 400 PB word lists. Similarly, a voice quality of 78 percent (400 PB word lists) is considered acceptable for military and industrial applications.

e. Data modem performance showed that the differentially coherent phase-shift keyed class of modems are a good choice for data transmission from satellite to ship at 1200 bps or higher. Error rates of 10^{-5} (uncorrected) were achievable for link C/N_o of 43 dB-Hz. Performance of the modem however was critically dependent upon the level of multipath received relative to the direct path carrier. It appears from these field results for data modems of the type tested plus the results of laboratory measurements that a C/M of 15 dB or more will be necessary to achieve bit error rates of 10^{-5} at C/N_o of 43 dB-Hz. Based on the carrier to multipath ratio measured concurrently during the tests, C/M of 8 to 11 dB is typical for the range of elevation angles, sea states, and antenna design used in these tests. Note, this is not inconsistent with the C/M values of 6-9 dB given in item d. above where antenna discrimination has not been taken into account. The 6 to 9 dB values refer to the estimated carrier-to- multipath power ratio in the electromagnetic wave as it impinges upon the antenna aperture, whereas the 8 to 11 dB values refer to the power ratio at the antenna output.*

f. Ranging modem precision in both modes of operation was in good agreement with laboratory simulator results. A precision of 500 ft. rms was achieved using the narrowband code.

g. The medium gain steerable antenna performed best in the slave mode. The autotrack mode experienced significant performance degradation at low elevation angles and/or high sea states due to multipath. A comparison of pointing error components in azimuth and in elevation showed that the slave mode gave a performance superior to that of the autotrack mode by a factor of three. Additionally, the autotrack mode is subject to the occurrence of an

*Polarization sense reversal not included in the 6 to 9 dB estimate.

occasional large pointing error due to the loss of receiver lock as a result of particularly severe multi-path.

h. The advantages of a coordinated USCG and FAA effort using satellites to interconnect widely dispersed aircraft and ships in a search and rescue operation were clearly demonstrated. The usefulness of satellites in conjunction with emergency notification procedures was borne out in demonstrating significant reduction in the distress alerting interval.

6. RECOMMENDATIONS

6.1 SYSTEM PERFORMANCE

The data presented in this report provides a basis for recommending an achievable performance specification for a maritime satellite communication system. Such a system would provide communication service to the USCG and achieve performance levels exceeding those of the systems currently in use. This satellite communication system would provide performance as follows:

a. Voice - 80 percent intelligibility at 43 dB-Hz.

b. Data - Bit error rate of 1×10^{-5} at 43 dB-Hz using 1200 b/s.

c. Combined voice and data - a single channel modem providing simultaneous voice and data. At 43 dB-Hz the voice intelligibility would be better than 70 percent and the data bit error rate would be less than 1×10^{-5}.

d. Ranging - Radio position determination accuracies of 20 80 feet in a channel bandwidth of 300 kHz and with a carrier-to-noise power density ratio as low as 36 dB-Hz.

e. Antenna - A medium gain (approximately 15 dB) antenna appears suitable for this application. The slave mode of tracking would be selected in those instances where an electrical signal (synchro or resolver) is available which corresponds to ships heading. A pitch derived signal is probably not needed and a roll signal of sufficient accuracy (a few degrees) could probably be made available through the use of a relatively inexpensive vertical reference. Such a reference might be developed to provide both roll and pitch signals.

6.2 TECHNOLOGICAL DEVELOPMENTS

6.2.1 Error Correction Coding

Forward correction coding is recommended for adaption to digital transmission on the satellite-mobile link. The purpose of

the coding would be to permit operation, with lower margin, at lower elevation angles between the ship and the satellite. Extended coverage would be achieved fo the same satellite capability.

6.2.2 Antenna Inertial Reference

This experiment showed that a directional antenna can be slaved to an inertial reference so as to provide a small pointing error through a wide range of ship motion. However, inertial references tend to be expensive when considering low-cost applications. Accordingly, a simple low-cost reference system is recommended for development which would be suitable for use on a wide variety of vessels.

6.3.3 Omni Antenna Tests

It is recommended that future tests be run to determine the suitability of an omnidirectional antenna for satellite communicatons. Such an antenna would generally not involve pointing stabilization, although simple roll stabilization might be appropriate in certain installations.

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